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13. ABSTRACT (Maximum 200 words)

The Optoelectronic Materials Center is a collaborative program involving the University of New Mexico, Stanford University, and the California Institute of Technology. Sandia National Laboratories and MIT Lincoln Laboratory are also involved in this program under separate contract vehicles. This program emphasizes three main areas:

- diode-based visible sources
- two-dimensional optical interconnects, and
- high-speed optoelectronics.

Progress on individual tasks is very briefly discussed below. Several of the tasks will impact more than one of the above areas. For simplicity, the tasks are arranged by institution in an order roughly determined by the above areas.

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OPTOELECTRONICS MATERIAL CENTER

A Collaborative Program including

Center for High Technology Materials
of the University of New Mexico

Stanford University

California Institute of Technology

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DARPA OMC QUARTERLY PROGRESS REPORT

October 1, 1992 - December 31, 1992

UNIVERSITY OF NEW MEXICO

CENTER FOR HIGH TECHNOLOGY MATERIALS

Visible Diode Lasers

High Power IR Lasers for Frequency Doubling to Visible Wavelengths

Our novel edge-emitting unstable-resonator semiconductor laser, which has been developed with partial support from AFOSR, is now showing single facet output powers up to 500 mW (pulsed at a 1 % duty cycle). Furthermore, these high output powers are achieved with a highly coherent output beam that can be focused[1]. MOCVD is used to fabricate the unstable resonator waveguide in these devices and to ensure a high quality regrown interface. This regrowth is confined to GaAs on GaAs. Measurements of threshold current density on these lasers show that the regrowth has a minimal impact, even though it is only 2000 Å from the active region. We are currently working on improving our Ohmic contact and bonding technology to allow higher power and CW operation of these devices. (Hersee)

Group III-Nitrides

The longer term solution will exploit the large and direct band-gap of group III-nitrides to fabricate visible lasers. Many issues remain to be addressed in these semiconductor alloys if we are to fully exploit their potential. We are currently addressing the role of microstructural defects in GaN structures. We are also developing a cross-sectional transmission electron microscopy (TEM) sample preparation technique that will allow the detailed examination of microstructure in these materials. (Hersee)

Vertical Cavity Surface-Emitting Lasers

The use of vertical cavity surface-emitting lasers as a source for high-speed optical interconnections was investigated. Single-mode VCSELs with excellent electrical characteristics were fabricated with a threshold voltage below 2V and an operating voltage of 2.6V at a full output amplitude of 1 mW. These were bonded in high-speed packages and were subjected to a peak-to-peak electrical modulation amplitude of 0.8V with a pre-bias near threshold (1.9V) that gives an optical output modulation between 0 an 1 mW. The optical output has a rise-time of about 50 ps and a fall-time of 200 ps. The latter is due to non-optimal implant isolation conditions. The devices were also

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[1]S.T Srinivasan, C.F. Schaus, S.Z. Sun, S.D. Hersee, and J. McInerney, *High Power single-lateral mode operation of unstable resonator semiconductor lasers with regrown lens train*, Applied Phys. Letts. 61 (11), Sept. 14, 1992, p. 1272.

modulated by 1 GB/s pseudo-random pulses with a non-return-to-zero format, using a similar pre-bias. The resulting eye diagram shows that large-signal electrical modulation at 1-2 GB/s is possible. These VCSELs are therefore suitable for multi-GB/s optical links. To illustrate that the VCSELs can be interfaced to electronics drivers, a VCSEL is used as the output load in a follower circuit using a high-speed HBT driver. Once again 1 GB/s pseudo-random voltage pulses are applied to the HBT. The modulated optical output pulses from the VCSELs show clearly that 1-2 GB/s modulation can be achieved. Both the optical and electrical gain-switching of VCSELs were also investigated. Optical output pulses as short as 26 ps have been achieved, which is further evidence that the VCSELs can be used as a very high-speed source. (Cheng)

Enhanced Long Wavelength Si MSM Detectors

Silicon technology dominates the microelectronics marketplace, while III-V-based technology is predominant in optoelectronics. Optical interconnections are widely viewed as a potential near-term application of optoelectronics to advanced computers. Among other issues, the necessity of a hybrid system adds cost and complexity. We have succeeded in extending the wavelength range of simple, VLSI compatible metal-semiconductor-metal detectors in the Ni:Si system using a simple ion-implantation step. The ion-implant results in a large density of defect states that dramatically increase the Si absorption. The strong fields associated with the MSM configuration allow collection of most of the photogenerated electron-hole pairs. Results include an effective internal quantum efficiency of 75% at 940 nm (the longest wavelength investigated, limited by the Ti:Al_2O_3 optics). This result is a factor-of-three better than for otherwise identical unimplanted devices. The detector speed, evaluated at 760 nm, showed an instrumentation-limited FWHM of less than 100 ps, and a much less pronounced *diffusion tail* than the unimplanted devices. (Brueck)

Thermal properties of two-dimensional arrays of PITSELs

Vertical-cavity surface-emitting lasers (VCSELs) are generating considerable interest due to their potential for integration into two-dimensional (2D) arrays. Efficient heat dissipation is critical for future applications such as optical interconnects, information processing, or neural networks, where massive integration is required. A major obstacle preventing development of electrically pumped 2D arrays today is their intense heating. We have examined limits on thermal dissipation in large-size 2D arrays of proton-implanted top-surface-emitting lasers (PITSELs). Planar GaAs/AlGaAs PITSELs emitting light through the top surface are very attractive for integration due to their relatively low series resistance and wavelength compatibility (and associated cascadability) with GaAs-based phototransistors or photothyristors.

We have investigate thermal properties of large-size arrays using the self-consistent thermal model developed to study individual PITSELs and described in our previous report. The analysis features realistic distribution of heat sources combined with 2D heat-flux spreading. Self-consistent solution is found by numerical iteration, taking into account temperature-dependence of device parameters. In particular, we have examined what improvement can be expected if a standard copper heat sink is replaced with diamond. We have shown that while a copper heat sink is sufficient to obtain a satisfactory performance of single emitters, large-scale integration can only be achieved using either a diamond heat sink, or an active cooling scheme. (Osinski)

Thermal properties of etched-well VCSELs

We have developed a new, improved version of our comprehensive self-consistent thermal-electrical model of etched-well double-heterostructure vertical-cavity surface-emitting lasers (VCSELs) with dielectric mirrors. Compared to the previous version, we have considered the heat source in the *p*-type spreading layer, simplified Joule heat source calculations by using analytical expressions, added an automatic accuracy check in calculation of the series expansion for temperature, and tabularized the Bessel functions in order to reduce the computing time. We then used the improved model to investigate thermal properties of GaAs/AlGaAs etched-well VCSELs. Special attention was paid to effects of varying the active-region diameter on thermal behavior of the device.

Most VCSEL structures exhibit increasing threshold current densities when device diameter is reduced below, say, 30 μm. Large diameter lasers experience smaller losses due to diffraction and diffusion, which results in lower thresholds. However, when the diameter is too large, the heating problems become more important since the heat dissipation becomes essentially one-dimensional. There is, therefore, a trade-off between reducing losses and maintaining efficient heat sinking, which leads to optimal device size. We have optimized the laser design with the goal of reducing the relative power loss due to heating and maximizing the optical output power. The optimal active-region diameter, such that the excess of pumping current over the cw lasing threshold at the corresponding active-region temperature is maximum, is 16 μm. (Osinski)

SANDIA

Low Resistance, Wavelength-Reproducible VCSELs Grown by MBE

We have succeeded in developing the technology for accurate, reproducible growth of DBR mirrors that have unprecedented low series resistances. This has been accomplished by growing "piecewise-linearly-graded" mirrors that have three linearly graded segments per interface, which results in interface potential barriers significantly reduced from those present in mirrors that have zero or one linearly graded segments per interface. We have shown that (AlGa)As DBR mirrors can be grown that have series resistances near bulk resistance values (as low as $1.8 \times 10^{-5}\ \Omega\ cm^2$ for a 20-period mirror). Our method is capable of producing mirrors with a center wavelength reproducibility of 0.1%, which is about an order of magnitude better than was previously possible. Measured reflectivities are in agreement with simulations, and are comparable to conventional single-linear-grade mirrors. We have shown that integration of these DBR mirrors into VCSELs results in devices with excellent operating characteristics. (Chalmers, Killean, Lear)

Photoassisted II/VI MBE and Nonlinear Optical Properties of CdTe and ZnTe

Photoassisted MBE has been employed as a method to enable substitutional doping of CdTe and ZnTe. Stoichiometric and metal-rich layers have been grown with and without laser illumination. The electronic characteristics of these films are currently under investigation. It has been determined that the growth of ZnTe on InAs requires a significantly lower growth temperature than is standard. The use of elemental sources rather than a compound source is being investigated as a solution, In collaboration with Kevin Malloy at UNM, the wavelength dependence of the nonlinear second harmonic coefficient has been measured between 700 and 1000 nm for CdTe and Zn Te. (Reno and Malloy)

STANFORD UNIVERSITY

Visible Light Sources:

Ultrafast Sampler

Our previous work on photodetectors has focused on GaAs based devices. This gave us the advantage of integrating other GaAs based circuits to build optoelectronic integrated circuits (OEICs) like 200 GHz GaAs photodiode-sampler circuit[2,3] and 2.0 ps photodetector-microwave detector circuit[4]. The sensitivity of the GaAs-based circuits has been limited to wavelengths shorter than 850 nm. In order to cover the longer wavelength (1.3 and 1.55 μm) region, which is of greater interest for telecommunication applications, we started developing a fabrication process to build InP-based OEICs.

Devices were grown on 2-inch diameter semi-insulating InP substrates. Growth starts with a thick, highly doped InAlAs, followed by an InAlAs/InGaAs superlattice that is used to obtain a graded heterojunction. This layer was followed by an undoped InGaAs layer that acts as the photoactive region. Another InGaAs/InAlAs superlattice is grown on top of the active layer to achieve the second graded heterojunction. The structure was completed by an undoped thin layer of InAlAs. The top InAlAs is used to obtain an enhanced Schottky barrier diode, as the Schottky barrier height of InGaAs is too low to achieve good quality Schottky diodes.

Our first generation photodiode circuits were designed around back-illuminated photodiodes, in which we use InP wafer and the InAlAs layer as the window elements. Although we were able get good Schottky diodes with high breakdown voltage and low leakage, the frequency response of the photodiodes was limited by the back-illuminated design, which resulted in relatively long hole transit times across the active region.

In order to improve the high frequency performance, we decided to change our back-illuminated design to a front-illuminated one. A semitransparent metal (100 Å thick) will be used to achieve the Schottky junction. Such a design will not be limited by the hole transit time. Besides, we can now use InGaAs, which is 5-10 times more conductive than InAlAs, as the conductive layer, resulting in a lower series resistance. These advantages come at the expense of absorption at the semitransparent Schottky metal, resulting in a lower responsivity. We have already finished the circuit design and mask layouts of the new InP-based OEIC and received our photomasks. Currently, we are waiting for the arrival of the new epitaxial materials to be used in our new process. (Bloom)

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[2]E. Ozbay, K.D. Li, and D.M. Bloom, *2.0 psec, 150 GHz GaAs Monolithic Photodiode*, Photon. Tech. Lett., vol. 3, p. 570 (1991)

[3]K.D. Li, A.S. Hou, E. Ozbay, J. A. Sheridan, and D.M. Bloom, Proc. Conference of Lasers and Electro-Optics, P. 608, 1991

[4]K.D. Li, A.S. Hou, E. Ozbay, B.A. Auld, and D.M. Bloom, *2-picosecond, GaAs photodiode optoelectronic circuit for optical correlation applications*, Appl. Phys. Lett., vol. 61, p. 3104 (1992).

CALIFORNIA INSTITUTE OF TECHNOLOGY

Nanometer-Scale Selective Growth of GaAs and InGaAs by OMVPE and Application to Quantum Size Effect Semiconductor Lasers

The OMVPE reactor for our quantum-structure work with DEGaCl selective epitaxy, located at the NASA Jet Propulsion Laboratory, has been modified extensively to meet the rigorous requirements of quaternary compound InGaAsP growth and to improve the current AlGaAs growth capabilities.

Temperature and pressure control on the OMVPE reactor has been improved by further modification, The new gas-injection manifold has been used to produce selectively grown materials by applying DEGaCl and arsine, including optical waveguide structures with virtually no defects occurring along five-millimeter-long one-micron-wide stripes. Uniformity of the stripes is also quite good. (Vahala)